THE HALLEY LECTURE, 1913

The Earth's Magnetism

By

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THE EARTH'S MAGNETISM*

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It is indeed a great privilege and pleasure to give a lecture at Oxford, where Edmund Halley, whose name the Founder has so wisely coupled with this Lectureship, laboured devotedly in the interest of science; and to be permitted, in some small measure, to pay the debt of Terrestrial Magnetism, and my own personal debt as well, to this illustrious investigator.

Halley's varied scientific activity and his wide sympathies were well set forth by the Halley Lecturer † of two years ago, who had as his subject an astronomical one—"The Stars in their Courses." The theme of last year's lecture,‡ "Large Earthquakes," by that zealous pioneer, Professor Milne, again exemplified both the scope of this Lectureship and the fact that Halley's interest and achievements in geophysical science, though not generally so well known as his astronomical discoveries, were no less great. The subject of the lecture to-night—"The Earth's Magnetism"—is one in which Halley's name stands out pre-eminent among the early students of the science. As it is a large subject and one in which there might be much discursive rambling, we shall do well to limit ourselves

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* The fourth "Halley Lecture," delivered in the Schools of the University of Oxford, on May 22nd, 1913; illustrated by lantern slides.

† Professor H. H. Turner, D.Sc., D.C.L., F.R.S., Savilian Professor of Astronomy, University of Oxford (see Bedrock, Vol. I., No. 1, April, 1912, pp. 88—107).

‡ Published in Bedrock, Vol. I., No. 2, July, 1912, pp. 137—156.

somewhat—to choose our starting point and then proceed in certain definite directions.

The adopted flag of the Chinese Republic consists of five stripes, partly because, as I am told, in China all good things are five—five seasons, five principal grains, five genii, five relationships that make up life, and five points of the compass: north, south, east, west, and *centre*. For, to the Chinese, the starting-out point is as important as the point to which, or direction in which, a journey is made. So it also must be with us to-night.

According to the regulations governing this lecture, it is to be known as the "Halley Lecture on Astronomy and Terrestrial Magnetism." "Astronomy shall include Astrophysics, and Terrestrial Magnetism shall include the physics of the external and internal parts of the terrestrial globe." This lecture might, therefore, with propriety cover the whole range of investigation in terrestrial and cosmical magnetism. However, we must limit ourselves to those particular lines of research in our subject in which Halley himself was chiefly interested. It so happens that these are the very lines also in which I have been given the opportunity to continue and expand the work begun by him.

After Halley had made two attempts to establish a working theory respecting the distribution of terrestrial magnetism and the cause of its striking change with the lapse of years—the so-called secular variation—he must have reached the conclusion that the elusive problem of the Earth's magnetism would be more profitably advanced by additional facts than by further speculation. That, paraphrasing Seneca, to avoid making a false calculation of matters, it were better to advise with Nature rather than with opinion. Accordingly we find him setting out in October, 1698, in command of a sailing ship, the *Paramour Pink*, and cruising in her under orders from the British Government, back and forth, north and south, in the Atlantic Ocean for two years, observing almost daily, sometimes several times in a day, the angle which the compass needle makes with the true north and south line—the angle known to the man of science as the magnetic declination, to the mariner and surveyor as the "variation of the compass."

This is memorable as being the first scientific expedition sent out by any country with the specific object of improving existing

knowledge regarding certain facts of the Earth's magnetism. Not until somewhat over two centuries later did it occur again, that a sailing ship traversed the oceans with the chief purpose of making magnetic observations.* In July, 1905, there sailed from the port of San Francisco, California, a chartered sailing yacht, the *Galilee*, sent under the auspices of the Carnegie Institution of Washington, on the sole mission to determine the magnetic elements at sea, for the benefit of both the mariner and the man of science, as was also the purpose of Halley's voyages. Four years later, in 1909, a specially built non-magnetic vessel, likewise under the auspices of the Carnegie Institution of Washington, left New York for St. Johns, Newfoundland, and thence proceeded to Falmouth, along practically the same track followed by Halley's ship. Since then this vessel, the *Carnegie*, has circumnavigated the globe and has repeatedly intersected the course of the *Paramour Pink* in the Atlantic Ocean.

In view of the historic interest thus attaching to Halley's magnetic expedition, it will be well worth our while to use this as our starting point or centre, the fifth point in the Chinese compass. The instructions given Halley, as far as they pertained to his observational work, were as follows :—

> "Whereas his Majesty has been pleased to lend his 'Pink the Paramour' for your proceeding with her on an expedition to improve the knowledge of the Longitude and variations of the Compasse, which shipp is now completely Man'd, Stored, and Victualled, at his Majesty's charge for the said Expedition : you are therefore hereby required and directed to proceed with her according to the following instructions :—
>
> "You are to make the best of your way to the southward of the Equator, and there to observe on the East Coast of South America, and the West Coast of Africa, the variations of the Compasse with all the accuracy you can, as also the true situation both of Longitude and Latitude of the Ports where you arrive.
>
> "You are likewise to make the like observations at as many of the islands in the seas between the aforesaid Coasts as you can (without too much deviation) bring into your Course ; and, if the season of the year permit, you are to stand soe farr into the South till you discover the Coast of the Terra Incognita, supposed to lie

* Valuable magnetic data have been secured by various expeditions since Halley's time, but either the magnetic work was merely incidental, or formed part of a general scientific programme, or was combined with some geographical object, such as Arctic or Antarctic exploration—the memorable *Erebus* and *Terror* expeditions, for example.

between Mongolan's Straits and the Cape of Good Hope, which Coast you carefully lay down in its true position. In your return home you are to visit the English West India Plantations or as many of them as conveniently you may, and in them make such observations as may contribute to lay them down truely in their Geographicall Situation. And in all the Course of your voyage you must be carefull to omit no opportunity of noting the variation of the Compasse, of which you are to keep a Register in your Journal."

Curiously enough, Halley, though a prominent member of the Royal Society, never contributed a paper to it, nor did he publish anything elsewhere, on these voyages of his, his observations, or resulting conclusions. Not until 1775 were Halley's journal and observations published, and then by Alexander Dalrymple in his *Collection of Voyages chiefly in the Southern Atlantick Ocean,* from the manuscript in the possession of the Board of Longitude at London. Halley appears to have contented himself with laying down the results of his work on a chart entitled "A new and correct Sea Chart of the Whole World, showing the Variations of the Compass as they are found in the year 1700." This chart is often briefly referred to under the title "Tabula Nautica." The first edition, published probably in 1701, covered only the ocean—the Atlantic—traversed by Halley himself; for the later edition, as the chart was now to cover the greater part of the globe, he had to collect and utilise observations made by others. No printed reference to the early edition, either by Halley or by anyone else, prior to my discovery of a copy in the British Museum in 1895, has thus far come to light. Yet this particular chart, termed by me the "Atlantic Chart," to distinguish it from the later one—the "World Chart"—is especially interesting, as it contains the routes followed by the *Paramour Pink.* Airy, when he reproduced Halley's "World Chart" in the Greenwich observations of 1869, was seemingly not aware of the "Atlantic Chart." *

The only description of Halley's chart by himself, thus far found, is that either attached to certain editions of the chart or contained

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* Those interested in the history of the Halley charts may be referred to the various articles by L. A. Bauer in *Nature,* May 23rd, 1895, p. 79, and in *Terrestrial Magnetism,* January, 1896, and September, 1913; the last named reference also contains a compilation of the magnetic results obtained on Halley's expedition.

on an accompanying leaflet. This, however, is very brief and was chiefly intended to instruct mariners in the use of the chart. Halley points out that in certain regions where the "Curves" run suitably, they may be used "to estimate the Longitude at Sea thereby." To his lines of equal "magnetic variation" he gave no distinctive name, simply referring to them as the "Curve Lines." Thus he says: "What is here properly *New*, is the *Curve Lines* drawn over the several Seas, to show the degrees of the *Variation* of the *Magnetical Needle*, or *Sea-Compass*." He does, however, use the term, "Line of No Variation." For some time these lines were referred to by others as the "Halleyan Lines." Hansteen, a century later, introduced the term, "isogonic lines," which is now generally adopted. According to Hellmann there is reason for believing that some attempts had been made before those of Halley to give on a globe or a map a graphical representation of the direction in which a compass needle points. It is conceded, however, that Halley's was the first successful attempt; his "variation chart" was the first magnetic chart based on sufficient observational data to give it immediately both practical and scientific value.*

After the publication of his chart—the most important contribution to the observation-material of terrestrial magnetism at the time—Halley made no further attempt to establish a theory or to improve on his early magnetic speculations. He appears finally to have adopted the view so clearly formulated by Professor Turner †:—

> "that the perception of the need for observations, the faith that something will come of them, and the skill and energy to act on that faith—that these qualities all of which are possessed by any observer worthy the name, have at least as much to do with the advance of Science as the formulation of a theory, even of a correct theory."

We find Halley embracing every occasion

"to recommend to all Masters of Ships, and all others, Lovers

* Mountaine and Dodson, the authors of the second and revised edition (1744) of the Halley Chart, and of the third (1756), published in connection with the latter a small tract: "*An Account of the Methods used to describe Lines on Dr. Halley's Chart of the terraqueous Globe, showing the variation of the magnetic needle about the year* 1756 *in all the known seas* . . . . London, 1758, 4°." This tract was again published in 1784.

† Pres. Address, Sec. A., Brit. Assoc. Adv. Sci., 1911.

of Natural Truths, that they use their utmost Diligence to make, or procure to be made, Observations of these Variations in all parts of the World, and that they please to communicate them to the *Royal Society*, in order to leave as compleat a History as may be to those that are hereafter to compare all together, and to compleat and perfect this abstruse Theory."

Consulting the minutes of the Royal Society, it is found that Halley communicated, from time to time, the results of magnetic observations received from various expeditions, as also the values of the magnetic declination observed by himself, at London, viz. :—

"1701, May 7.—Mr. Halley tried the experiment of the Variation of the Needle this day, with the two needles he had with him in his late Voyage : and by the one the Variation was 7° 40′, by the other 8° 00′ W.

"1702, July 8.—Mr. Halley observed the Variation of the Needle, which was found to be 8½° Westward, or very near it.

"1716, May 24.—Dr. Halley reported that he had drawn a Meridian Line on the stone erected in the Society's yard before the repository and that the Variation was found at present to be full twelve degrees."

These observations of the magnetic declination of 1701, 1702, and 1716 are perhaps printed here for the first time and are not found in any of the compilations of magnetic declinations at London published thus far. Only Halley's earlier observations, namely, those of 1672 (2° 30′ W.), 1683 (4° 30′ W.), and of 1692 (6° 00′ W.), having been given by Halley himself in his printed papers of 1683 and 1692, have become known to compilers.

Change of the Magnetic Declination in the Atlantic Ocean since Halley's Chart.

In view of the fact that the two vessels—the *Paramour Pink* and the *Carnegie*—both being primarily dependent for their motive power upon the prevailing winds in the Atlantic Ocean, have followed nearly identical courses, it will be a matter of no little interest to compare the values of the magnetic declination given on Halley's chart for 1700 with those obtained by the *Carnegie* in her cruises of 1909—10. We find first that over the entire Atlantic, from 50° N. to 40° S., the north end of the compass needle in 1910 was to the west of the compass direction of 1700, by amounts varying with locality. Thus for various important ports the

approximate change was as follows: New York, 2°·9 W.; St. Johns, Newfoundland, 14°·6 W.; Falmouth, England, 10°·4 W.; Funchal, Madeira, 15°·6 W.; Bermuda, 10°·5 W.; Porto Rico, 7°·6 W.; Para, Brazil, 14°·6 W.; Rio de Janeiro, 20°·8 W.; Buenos Aires, 13°·0 W.; Cape Town, 16°·2 W.

If we follow a line passing through the points of maximum change in the Atlantic Ocean, we find for the following points:—

VALUES OF THE MAGNETIC DECLINATION IN 1700 AND 1910.

Latitude.	Longitude.	*Paramour Pink*, 1700.	*Carnegie*, 1910.	Secular Change (1910–1700).
50°·4 N.	30°·4 W.	11°·3 W.	29°·5 W.	18°·2 W.
35°·9 N.	47°·0 W.	4°·0 W.	22°·1 W.	18°·1 W.
21°·0 N.	30°·9 W.	0°·6 W.	19°·2 W.	18°·6 W.
5°·9 N.	35°·8 W.	2°·5 E.	16°·5 W.	19°·0 W.
40°·6 S.	25°·2 W.	10°·7 E.	17°·5 W.	28°·2 W.

We see, accordingly, that the compass direction, in the course of time, suffers large changes; for the region and time-interval considered the changes vary from about 3° off New York to 28° in the Atlantic Ocean about midway between Buenos Aires and Cape Town. Even these amounts may not represent the total or maximum change during the period in question.

Equally to be noted with these large changes with time is the important fact that the *amount of change* is as dependent upon locality as is the prevailing compass direction itself, which for over four centuries has been known to be anything but "true to the pole."

We have thus had impressed upon us this important fact: Two sailing vessels cruising in the Atlantic Ocean from port to port—the one in 1700 and the other in 1910—were forced by the prevailing winds to follow very closely identical courses. If, however, these two vessels had been directed to follow certain definite magnetic courses, and if we may suppose that they had such motive power as to render them independent of the winds, then their respective paths would have diverged considerably. For example, if the *Carnegie* had set out from St. Johns, Newfoundland, to follow the same magnetic courses as those of the *Paramour Pink*, instead of

coming to anchor in Falmouth Harbour, she would have made a land-fall somewhere on the north-west coast of Scotland. In brief, while the sailing directions as governed by the winds over the Atlantic Ocean are the same now as they were during Halley's time, the magnetic directions or bearings of the compass that a vessel must follow to reach a given port have greatly altered. To quote from the suggestive essay on Terrestrial Magnetism by John F. W. Herschel: *

> "The configuration of our globe—the distribution of temperature in its interior—the tides and currents of the ocean—the general course of winds and the affections of climate—whatever slow changes may be induced in them by those revolutions which geology traces—yet remain for thousands of years appreciably constant. The monsoon, which favours or opposes the progress of the steamer along the Red Sea, is the same which wafted to and fro the ships of Solomon. Eternal snows occupy the same regions, and whiten the same mountains—and springs well forth at the same elevated temperature, from the same sources, now as in the earliest recorded history. But the magnetic state of our globe is one of swift and ceaseless change. A few years suffice to alter materially, and the lapse of half a century or a century to obliterate and completely remodel the form and situation of those lines on its surface, which geometers have supposed to be drawn, in order to give a general and graphical view of the direction and intensity of the magnetic forces at any given epoch."

Regarding Longitude Determinations at Sea.

One important result of Halley's voyage and of the publication of his chart was the awakening of renewed interest in the improvement of methods for determining the longitude at sea. Recalling Halley's instructions, we note that one of the objects of his expedition was "to improve the knowledge of the Longitude."

When the discovery was made that the magnetic declination varied from place to place, the idea immediately occurred to Columbus, as also to Cabot, that the longitude might be determined at sea by means of this fact. Antonio Pigafetta, who accompanied Magellan on his first voyage around the world in 1522, definitely proposed, in his book on navigation, this method of longitude determination. The line of no magnetic declination, which at that

* *Essays from the Edinburgh and Quarterly Reviews, with Addresses and Other Pieces*, by Sir John F. W. Herschel, London, 1857, pp. 69—70.

time passed through the Azores, was regarded as the natural meridian from which to count longitude. When later it was found, as was first remarked by J. de Acosta in his *Historia Natural . . . Sevilla*, 1590, that there were four such lines, it was again thought that these quadrantal divisions could be utilised for reckoning longitudes. In 1674 Charles II. appointed a commission to examine into the pretensions of a scheme devised by Henry Bond for ascertaining the longitude by the "variation of the compass."

Halley's chart, however, definitely showed that it would be, in general, futile to attempt to determine the longitude by means of an element so variable and so irregular in its distribution as is the magnetic declination. Nevertheless, the hope that some magnetic phenomenon might yet serve to aid in the solution of this problem did not die immediately.

In 1721 we find William Whiston, Newton's successor at Cambridge, installing dip circles on a number of vessels, with instructions to observe diligently the magnetic dip in order to determine whether by means of this element the longitude could be better found at sea than by the magnetic declination; he likewise hoped thus to determine the latitude at sea.

It is also interesting here to note that when Dr. Johnson was at Oxford, he gave in 1756 to the Bodleian Library a thin quarto of twenty-one pages, entitled *An Account of an Attempt to ascertain the Longitude at Sea by an exact Theory of the Variation of the Magnetical Needle, etc.*, by Zachariah Williams, published at London in 1755; Johnson entered it with his own hand in the Library Catalogue. Boswell relates that Johnson himself wrote the English version for Williams, and, in order to make it more extensively known, also had an Italian translation prepared by his friend, Signor Baretti.

For fully three centuries the idea that the longitude could be determined at sea with the aid of some magnetic element, though proved to be fallacious, served a most useful purpose by furnishing the necessary incentive to observe the magnetic elements. This is a striking illustration of the soundness of the position taken by Maxwell when he said: "I never try to dissuade a man from trying an experiment; if he does not find what he wants, he may find out something else." It was indeed true of these magnetic longitude

seekers, that they failed in their purpose, but they contributed data of inestimable value to the advancement of our knowledge of the Earth's magnetism.

Before leaving this subject it might be said that Halley himself proposed an astronomical method for solving the longitude problem and, with Newton, he was responsible for the Act of 1714 offering a reward to any person who should devise a satisfactory method for the determination of the longitude at sea. He also improved some of the instruments used in navigation.

Another result of Halley's various voyages deserves mention here, though not immediately concerned with the subject of our lecture, namely, his theory of the cause of the trade winds.* On certain editions of his "Variation Chart," there was given, in addition to the lines of equal magnetic variation, a "View of the Generall and Coasting Trade Winds and Monsoons or shifting Trade Winds."

Complexity of the Earth's Magnetism.

Reference has already been made to Halley's attempts, before his magnetic expedition, to establish a theory respecting the phenomena of the compass needle. Thus in 1683 he published in the *Philosophical Transactions* of the Royal Society "A Theory of the Variation of the Magnetical Compass," and in 1692, in the same *Transactions*, "An Account of the Cause of the Change of the Variation of the Magnetic Needle."

In these papers Halley rejected the hypothesis which had been accepted up to that time and on the basis of which elaborate tables of the magnetic declination had been constructed by previous investigators, namely, that the directions assumed by a compass needle in various parts of the Earth could be accounted for by a simple magnetisation parallel to a diameter so that the magnetic poles would be diametrically opposite to each other. While the conclusion reached by him that "the whole Globe of the Earth is one great Magnet having four Magnetical Poles, or Points of Attraction, near each Pole of the Equator Two," has, in a certain sense, been found to be incorrect, nevertheless, this view appears to have been the first definite recognition of the heterogeneity or complexity of the Earth's magnetic condition.

* See *Miscellanea Curiosa*, Vol. I., pp. 61—80, and Pl. 2.

The increased knowledge gained from magnetic surveys since Halley's time has taught that the more carefully a country has been explored, *i.e.*, the nearer together the points at which the magnetic elements have been determined, the greater is the number of irregularities usually shown by the so-called isomagnetic lines ; indeed, regions have been found where no system of lines can adequately and correctly represent the prevailing magnetic conditions. We have learned that the regularities in the distribution of the Earth's magnetism, far from being normal features, as was once thought, are, instead, the abnormal ones, and that the irregularities are the normal and to-be-expected phenomena.

The magnetic forces, as measured at any given point on the Earth's surface, appear, according to various analyses, to be the resultant effects of : (1) a general or terrestrial magnetic field due to the general magnetic condition of the whole Earth ; (2) a general terrestrial disturbing cause which distorts at the place of observation the general magnetic condition of the Earth ; (3) a disturbing effect continental in extent ; (4) a regional disturbance effect due to low-lying magnetised substances ; and (5) a local disturbance due to the magnetised masses in the immediate vicinity.

No formula has as yet been established which will represent the observational facts within the error of observation, in fact not even with sufficient accuracy for the practical purposes of the surveyor and of the mariner.

The Earth's Magnetic Poles.

We have noticed that Halley, as the result of his study of the observations of the magnetic declination, as far as they had become known up to 1683, reached the conclusion that the Earth had "four Magnetical Poles, or Points of Attraction." Some confusion has arisen as to the precise meaning which Halley attached to his "Poles." Owing to his alternative term—"Points of Attraction" —certain eminent writers have sought to identify Halley's supposed four Magnetic Poles with the four *foci* of maximum total magnetic force, whose existence appeared to be indicated when, near the middle of the nineteenth century, it became possible to construct a chart of the lines of equal magnetic force. By this incorrect inference these authors have unwittingly credited Halley with a discovery which,

in the absence at the time of any observation whatsoever respecting the strength of the Earth's magnetic force, he could not possibly have made. The real merit and purport of Halley's deduction has thereby been obscured. The observation-material at Halley's disposal, before he himself enriched the material during his voyages, consisted of some miscellaneous observations of the compass direction and a few values of the magnetic dip. As has been said, there were no observations of the magnetic force, for the art of measuring this element had not yet become known.

Scrutinising carefully his scanty observation-material, Halley noticed that the direction of the compass needle did not change from place to place in the simple way it would if, for example, the Earth had two Magnetic Poles diametrically opposite each other. In the latter case, the needle would set itself tangent to the great circle passing through the Magnetic Poles and the place of observation. If, then, the compass direction were known at two places, sufficiently far apart, the points of intersection of the two great circles drawn respectively tangent to these compass directions would be the two diametrically opposite Magnetic Poles. It is such points of intersection—"points of convergence," as Hansteen later called them—which Halley had in mind as "Magnetic Poles." He was the first to perceive clearly the fact—abundantly verified since—that the various points of convergence as found from successive pairs of compass directions, in the manner just described, do not fall together as they should on the basis of a simple or regular magnetisation of the Earth. However, it appeared to Halley, and the same conclusion was reached over 100 years later by the illustrious Norwegian magnetician, Hansteen, that the several points of convergence grouped themselves, in a general way, about two main centres,

> "near each Pole of the Equator Two; and that, in those parts of the World which lie near adjacent to any one of those Magnetical Poles, the Needle is govern'd thereby, the nearest Pole being always predominant over the more remote."

It will not be well to lay greater stress upon this deduction, nor upon those in his 1692 paper, where he seeks to account for the existence of his four "Magnetic Poles" and for the secular variation, than to say that Halley drew the best possible conclusions the material at his disposal permitted. In fact, his conclusions were not materially

improved upon until a century and a half later, when a much more complete knowledge of the distribution of the Earth's magnetism had been gained, and when the various mathematical attempts which had been made to compute the magnetic elements, on the basis of more or less intricate hypotheses as to the Earth's magnetisation, had been found to be inadequate. Some later investigators, indeed, might have spared themselves considerable pains had they previously familiarised themselves more thoroughly with Halley's work.

When we to-day speak of the Earth's Magnetic Poles, it is generally recognised that those points on the Earth's surface are meant where the dipping needle stands precisely vertical and where the magnetic dip is, accordingly, 90°. This definition permits, with the aid of the dipping needle, of a precise determination of the Magnetic Poles, though, of course, it must not be understood that these Poles are mathematical points ; the area over which the dip may be found to be 90°, within the instrumental means of determination, may, in fact, be several miles square. A more or less extensive magnetic survey of the region round about would be required to eliminate the possibility of disturbing influences owing to local deposits of iron-ore. At these "Poles," since the magnetic force exerted by the Earth is all up and down, with no side component, a compass needle would have no directive force acting upon it. Some distance before reaching the Magnetic Pole it would become sluggish, and directly over the Pole itself it would be of no more use than a brass needle to indicate any definite direction.

Excluding for the present the purely "local magnetic poles" caused by extraordinary local deposits of attracting masses, all observations to date show that there are but two such points (or areas) where the dipping needle stands vertical, one in the Northern Hemisphere, located by Captain James Clark Ross, in June, 1831, in latitude 70°·1 N. and longitude 96°·8 W.* and the other in the Southern Hemisphere, lying, according to the observations of the recent Antarctic expeditions, about in latitude 72°·7 S. and

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* During Captain Amundsen's completion of the *Northwest Passage*, 1903—07, he also made observations with a view to locating the North Magnetic Pole, but the resulting position has not yet been published.

longitude 156° E. The Magnetic Poles, therefore, are, on the average, about 1,200 miles from the geographical poles. Owing to the asymmetrical distribution of the Earth's magnetism, the Magnetic Poles are not diametrically opposite each other, even if the positions given applied to the same year ; in fact, the perpendicular distance from the Earth's centre to the chord connecting the Magnetic Poles is about 750 miles.

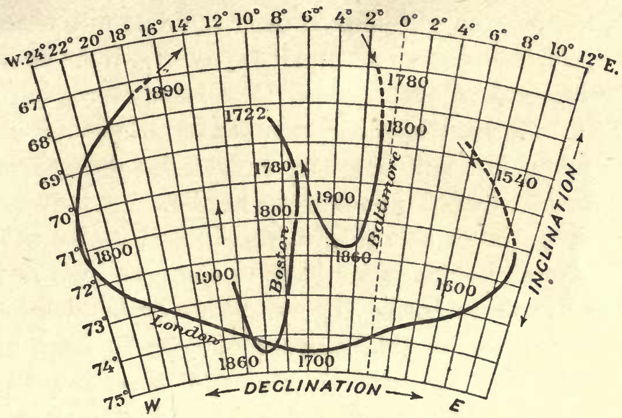
Let us suppose now that one explorer starts out from Oxford, where the compass points at present about 16° west, and follows always the direction shown by the north end of the compass needle, whereas another starts north from Washington, where the compass bears about 5° west, and follows likewise the direction of the compass needle. The paths thus traced out by them are the so-called "magnetic meridians," which, owing to the irregular way in which the Earth is magnetised, would not be straight lines or arcs of great circles, but more or less devious lines. Could these magnetic meridians be followed into the Arctic regions, they would be found to intersect at the North Magnetic Pole.

Owing to the irregular distribution of the Earth's magnetism, the points of greatest intensity of the total magnetic force depart widely in their locations from the Magnetic Poles. Thus there are in the Northern Hemisphere two distinct maxima of total magnetic force, one in the north-east of Siberia and the other in Canada to the south-west, approximately, of Hudson's Bay. A magnetic survey of the latter region is being made this summer by an expedition sent out by the Department of Terrestrial Magnetism.

Do the Magnetic Poles move ?

Possibly the most frequent question asked of those engaged in magnetic work is : "Do the Magnetic Poles move with the lapse of years, and if so, why ?" Unfortunately, as has already been shown, there are no direct observations as yet on which to base a definite statement. But it would be singular, indeed, if these points remained fixed and were not affected by fluctuations such as are now known from three centuries of observations to exist in every one of the Earth's magnetic phenomena. It is quite possible, in fact, that the Magnetic Poles pass through certain motions even in the course of a day or suffer displacements during magnetic storms.

The diagram below shows the changes in the direction of the compass (magnetic declination), as well as in the direction of the dip needle (magnetic inclination), as far as known, for London, Baltimore, and Boston. Imagine yourself, if you will, standing at the centre of a great magnetised needle so suspended as to be free to assume the direction actually taken by the lines of magnetic force at the place of observation, and let us suppose you are looking towards the north-pointing end of the needle. Could you gaze long enough, you would see a curve described in space by the observed end of the needle. This curve would lie on a sphere whose radius



Curves showing the Secular Change in the Magnetic Declination and in the Dip at London, Boston, and Baltimore. [Drawn for supposed length of freely suspended magnetic needle of about 50 centimetres, or nearly 20 inches.]

is the half-length of the suspended needle and for graphical representation we may take a central projection of it on a plane tangent to the sphere at about the middle point of the curve. The curves here given were constructed by me with the aid of the accumulated observations up to about 1895; the course followed by the needle since 1895 will be discussed later.

A number of interesting and instructive facts follow from these curves; time will permit us to give our attention only to the chief ones. It is seen that at London, for example, the compass reached its maximum easterly direction of about 11° in the year 1580, hence during the middle of Queen Elizabeth's reign; thereafter the easterly direction began to diminish until about 1658, the year of

Cromwell's death, when the needle bore due north and then swung over to the west, continuing to do so until it reached a maximum westerly direction of somewhat over 24° in about 1812. Hence in the interval of about 232 years (1850—1812) the compass direction changed at London from 11° E. to 24° W., or 35°. At the present time it points about $15\frac{1}{2}$° W., or nearly 9° less than in 1812, and a most interesting question doubtless immediately occurs to all of us : Will the freely suspended magnetic needle ever return precisely to a direction taken at some previous time or is there any definite cycle of changes which will repeat itself from time to time ?

Here again no wholly definite answer can be given, primarily because of the fact, as will be seen from the diagram, that, if there be such a cycle, it embraces many more years than are covered thus far by the interval of observation. For some European stations, *e.g.*, Paris and Rome, the observation-interval is somewhat longer than at London, but still not long enough for definite prediction as to the future course of the magnetic needle.

The diagram shows also that in the United States the changes in the compass direction, as far back as they are known, have not been as great as those during the same time at London. Thus, at Baltimore, for example, the compass appears to have reached a maximum westerly amount of about 6°·1 near 1670, and a minimum of $\frac{2}{3}$° in 1802, after which, instead of passing through a zero value as at London in 1658, and swinging to the eastward, it turned back and began to increase its westerly direction until at the present time the amount is about $6\frac{1}{2}$°. Thus, at this station the compass direction passed from a maximum to a minimum in about 132 years and the total change was but $5\frac{1}{2}$°, or only one-sixth to one-seventh of that at London.

In brief, the facts revealed by the known compass changes in my country cannot be brought in harmony with those witnessed in your country, unless we assume that the length of the cycle of complete change is many times longer than merely twice the period between a maximum and a minimum bearing of the compass. There are evidences, furthermore, into which we cannot go here, to indicate that the cycle of change at one station is not of the type which would result were we to close the apparently nearly completed curve at London by uniting the two ends in some simple manner.

On the contrary, the evidences point to cycles within cycles and to the probability that the secular variation curve, instead of being a single closed curve, may consist of smaller loops within a larger one, etc.; it is even questionable whether there ever will be exact closure of the curve.

There is at present another matter of no little interest with regard to England which should be pointed out here. It will be seen from the London curve that the dip of the needle below the horizon reached its maximum amount of 74°·4 in about 1688. At this time the compass changed its direction the maximum amount of 13′ per year. The curve would seem to indicate that the time of a minimum dip is now approaching; this phase has already occurred at Pawlowsk and seems to be now taking place at Potsdam and is travelling westward. Whether it will reach London and when cannot be answered definitely. However, it is a matter of no little interest, in this connection, to observe that the annual amount of change in the compass direction has in recent years received a remarkable acceleration in this part of the Earth. Thus, as is shown by the magnetic observatory records, it has almost steadily risen from 4′ per year in 1902 to about 9′ per year in 1912! Whether this portends an early approach of the phase of minimum dip at London is one of the many interesting questions continually arising respecting the perplexing phenomena of the Earth's magnetism. The course of the needle since 1890 has been about as shown by the arrow; thus in 1910 the magnetic declination was approximately 15°·9 W. and the dip was 66°·9.

One thing more. Note that for each of the three curves as far as drawn, the motion of the freely suspended magnetic needle has been clockwise, *i.e.*, the same as the motion of the hands of a watch. This fact, as shown by the curves in other parts of the world, constructed with the aid of the available observations, appears to hold generally in both the Northern and Southern Hemispheres, except for certain retrograde motions which thus far have not been of the same extent as the direct one, although, of course, it is not affirmed that they may not become so later. Such retrograde motions are at present being experienced in certain parts of the United States. Thus, for example, the compass pointed in 1910, 6°·25 W. at Baltimore and 13°·35 W. at Boston, and in the same year the magnetic

dip was 70°·9 at Baltimore and 73°·1 at Boston. If we plot these values on the diagram, we shall find that the curves for Boston and Baltimore, instead of progressing in the direction of the arrows, passed through a secondary crest about 1895 and then bent over to the left; how long this will continue cannot be foretold. [Several slides in illustration of the various facts of the secular change were shown.]

The question as to the cause of the remarkable changes from time to time in the Earth's magnetic condition, as indicated by these curves, has been a fruitful source of speculation since 1634, when Gellibrand definitely proved the fact that the compass direction varies from year to year. Some of the best minds have been engaged with the discovery of the cause, but the riddle is still unsolved. Hence, as regards the actual motions of the Earth's Magnetic Poles and the precise cause or causes, we may still say with Halley that these are "Secrets as yet utterly unknown to Mankind, and are reserv'd for the Industry of future Ages."

A mathematical analysis of the accumulated material shows that, in order to find an adequate explanation of the secular variation of the Earth's magnetism, we must reckon with systems of magnetic or electric forces having their seats both below and above the Earth's crust. There would also appear to be some evidence that, in addition to a motion of the Magnetic Poles or magnetic axes of the Earth, we may also have to take into account a possible diminution in the Earth's magnetic moment or intensity of magnetisation.

The Origin of the Earth's Magnetism.

Before concluding this lecture, we ought, perhaps, in the few minutes remaining, to say something regarding the status of the ever-recurring question as to the origin of the Earth's magnetism. Assuming that the magnetism of our planet is uniformly distributed throughout its mass, it is found that the average intensity of magnetisation is only about $\frac{1}{10000}$ of very highly magnetised hard steel. Professor Fleming, in his very suggestive popular lecture on the "Earth, a Great Magnet," given at the meeting in 1896 of the British Association for the Advancement of Science, made this statement:—

> "Taken as a whole, the Earth is a feeble magnet. If our globe were wholly made of steel and magnetized as highly as an

ordinary steel-bar magnet, the magnetic forces at its surface would be at least 100 times as great as they are now. That might be an advantage or a very great disadvantage."

If, however, we could penetrate the Earth's crust, we would find at a distance of only about 12 miles a temperature so great that, according to present laboratory facts, all magnetisation would necessarily cease. Hence, if the Earth's magnetic field arises from an actual magnetisation of the substances composing the Earth, these substances must be confined within a comparatively thin shell. But the question immediately arises: Is this argument correct? May it not be that just as the point of liquefaction is raised by increased pressure, so is also the critical temperature of magnetisation. It may thus occur that the effect due to increase of pressure with depth of penetration more than balances that due to increased temperature. There are at present no wholly decisive experiments which may be drawn upon to answer this query.

The hypothesis that the Earth may be an electromagnet also meets with difficulties when we attempt to account for the origin, direction, and maintenance of the required currents. In spite of the accumulated facts of over three centuries, we are still unable to say definitely to what the Earth's magnetic field is really due. Perhaps we may not be able to solve the riddle until the physicist answers for us the questions: What is a magnet? What is magnetism, in general?

In the *Devil's Dictionary* by Ambrose Bierce, published in 1911, the following definitions are given: "Magnet, *n.*—Something acted upon by magnetism. Magnetism, *n.*—Something acting upon a magnet." In explanation the author cynically remarks: "The two definitions immediately foregoing are condensed from the works of 1,000 eminent scientists, who have illuminated the subject with a great white light, to the inexpressible advancement of human knowledge." *

* These definitions and accompanying remarks may have had their origin in the following interesting anecdote told in the American *Review of Reviews* for August, 1909, of the late Professor Simon Newcomb, by Mr. A. E. Bostwick, associate editor of the *Standard Dictionary.* Of the definitions in physical science for this dictionary, Newcomb had general oversight, and on one occasion he took exception to the definitions framed for the words "magnet" and "magnetism," as based, in the absence of authoritative knowledge of the causes, simply upon the properties manifested by the things. After

A line of thought first suggested by Schuster and Lord Kelvin, that every large rotating mass, due to an as yet undiscovered cause, may be a magnet, should be considered in conclusion, though we may do so but briefly. If this be true, then magnetism is not confined to our planet alone, but all celestial bodies are surrounded by magnetic fields. Thus far no laboratory experiment, possibly owing to lack of required sensitiveness in the measuring instruments, has detected any magnetic field arising solely from rotation. Schuster and Swann have recently discussed the character and magnitude of the effects from the possible causes which may operate if the Earth's magnetic field be related in some manner to its rotation.

In 1900—03 Sutherland propounded a theory for the origin of the Earth's magnetism, which, briefly stated, is this : We know that electricity is an essential constituent of matter and that in every atom, if it be electrically neutral, there are equal amounts of negative and positive electricity. So with the whole Earth. Since it is almost electrically neutral, suppose that the total negative charge, while practically equal to the total positive one, occupies a slightly different volume from that of the positive charge, or, in brief, that the volume densities of the two body charges differ slightly. Then, because of the rotation of the electric charges with the Earth, a magnetic field arises. I have recently repeated Sutherland's calculations and, as I had previously found that the Earth's intensity of magnetisation increased systematically towards the equator, I have included a term to represent a possible effect similar in its distribution to that arising were the Earth's centrifugal force the operating cause. The computations show that to satisfy the known phenomena of the Earth's magnetism, the volume density of the negative charge must be smaller than that of the positive, or, in other words, the Earth's total negative charge must be distributed through the larger sphere, and, if that be the whole Earth itself, then for the chief term involved in the magnetic potential, the surface of the sphere containing the positive charge need be, on the

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writing and erasing alternately for an hour or more, he finally confessed, however, with a hearty laugh, that he himself could offer nothing better than the following pair of definitions : *Magnet,* a body capable of exerting magnetic force, and *Magnetic Force,* the force exerted by a magnet.

average, only $0{\cdot}4 \times 10^{-8}$ cms., *i.e.* four-tenths of the radius of an ordinary molecule, below that of the Earth's surface to give a magnetic field of the required strength. Taking the average atomic weight of the Earth's substance in round numbers as 50, the mean volume density of either charge would be about $3{\cdot}3 \times 10^{12}$ electrostatic units.

At present there is little hope that a magnetic field, caused just as supposed, can be detected in the laboratory. For a sphere of 15 cms. radius, rotating 100 times a second, the magnetic intensity at the poles would be but one hundred-millionth part (10^{-8}) of that of the Earth. We thus see that the quantities involved in the solution of one of the great problems confronting the student of the Earth's physics—the origin of the Earth's magnetic field—may be of such a minute order as to be beyond the ken at present of the laboratory experimentalist. Perhaps the effects become appreciable in the case of the Earth because of the fortunate fact that it is a body of sufficient size and angular velocity.

On the other hand, the geophysicist is at a great disadvantage in that he is unable to bring his Earth-magnet into the laboratory and to experiment upon it—to reverse the direction of rotation, for example, and see what would happen! Fortunately for him, however, Nature comes to his relief somewhat and performs experiments for him on his great magnet on a world-wide scale, by producing in an incredibly short time, manifold, and at times startling variations and fluctuations in the apparently fixed magnetisation of the Earth. Thus, on September 25th, 1909, there occurred the most remarkable magnetic storm on record, during which, within a few minutes, the Earth's magnetic moment, or intensity of magnetisation, was altered by about one-twentieth to one-thirtieth part. The Earth's magnetic condition was below par for fully three months thereafter. As this severe storm was accompanied by a brilliant display of polar lights, this is the most appropriate place to recall that Halley made the first suggestion of a connection between the *aurora borealis* and the Earth's magnetism.

It is firmly believed that a long step forward will have been taken toward the discovery of the origin of the Earth's magnetism when once we have found out what causes it to vary in the surprising manner shown by the secular or long-period changes, by the magnetic

storms, and by the numerous other fluctuations, such as the diurnal variation, for example. The keynote of modern investigation in terrestrial magnetism, as in the biological sciences, must surely be the study of the variations and mutations!

Is it not probable that the very features of the Earth's magnetism regarded at one time as defects—the "constant inconstancies," as an early writer quaintly put it—will instead become sources of help and inspiration from totally different points of view or in some entirely different line of thought? Who knows of what import the riddles of the Earth's magnetism, characterised by eminent physicists as being, next to gravity, the most puzzling of natural forces, may be, not simply to the magnetician alone, but to all interested in the steady progress of the physical sciences? Thus Schuster suggests that "atmospheric electricity and terrestrial magnetism, treated too long as isolated phenomena, may give us hints on hitherto unknown properties of matter." "The field of investigation into which we are introduced," says Maxwell, "by the study of terrestrial magnetism, is as profound as it is extensive." And, says Sabine, one of England's greatest and most enthusiastic magneticians: "Viewed in itself and its various relations, the magnetism of the Earth cannot be counted less than one of the most important branches of the physical history of the planet we inhabit."

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